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Life after Lead: Effects of Early Interventions for Children Exposed to Lead†

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Lead pollution is consistently linked to cognitive and behavioral impairments, yet little is known about the benefits of public health interventions for children exposed to lead. This paper estimates the long-term impacts of early life interventions (e.g., lead remediation, nutritional assessment, medical evaluation, developmental surveillance, and public assistance referrals) recommended for lead-poisoned children. Using linked administrative data from Charlotte, NC, we compare outcomes for children who are similar across observable characteristics but differ in eligibility for intervention due to blood lead test results. We find that the negative outcomes previously associated with early life exposure can largely be reversed by intervention. (*JEL* I12, I18, I21, J13, J24, Q51)

Lead (Pb) pollution is a pervasive threat to childhood health and development since it is associated with substantial cognitive and behavioral impairments. Despite a dramatic decline in the prevalence of lead due to the prohibition of leaded gasoline, lead exposure is still widely recognized as a major public health issue. Jacobs et al. (2002) estimate that one out of every four homes in the United States contains a significant lead paint hazard. In 2000, the World Health Organization estimated that 40 percent of children under 5 years old have levels of exposure associated with neurological damage, with 97 percent of these children living in developing countries (Prüss-Üstün et al. 2004). As is the case with other environmental hazards, lead is heavily concentrated in disadvantaged communities and therefore contributes to the intergenerational transmission of inequality through its impact on early life health (Aizer and Currie 2014).

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Given the large body of evidence connecting childhood lead exposure to cognitive and behavioral deficiencies,[1] the United States Center for Disease Control (CDC) recommends blood lead testing for children around one and two years of age and a case management approach for children whose detected blood lead levels (BLLs) exceed an alert threshold. To reduce childhood exposure and mitigate long-term damage, public health officials implement a combination of actions to both remove lead exposure through information and remediation as well as provide additional health and public assistance benefits for lead-poisoned children.

We merge blood lead surveillance data, public school records, and criminal arrest records at the individual level to evaluate the long-term impact of elevated BLL interventions on school performance and adolescent behavior in Charlotte, North Carolina.[2] Similar to that of many other state and local health departments, the public health response in North Carolina is based on CDC guidelines. Two consecutive test results over an alert threshold of ten micrograms of lead per deciliter of blood (μg/dL) triggers an elevated BLL intervention. Individuals exceeding this threshold for only one BLL test result are not eligible for the elevated BLL intervention.

To identify a causal impact of elevated BLL interventions, we compare a range of behavioral and educational outcomes between our intervention-eligible group—those with an initial and confirmatory BLL test over the alert threshold of 10 μg/dL—and a control group. We choose a control group with similar initial BLL test results, but whose confirmatory test falls just below the alert threshold (between 5 and 10 μg/dL). This group is very similar to those eligible for intervention across a wide range of observable characteristics. In our setting, a regression discontinuity model is not ideal due to a small number of observations around the threshold and a growing intensity of the intervention as BLL results increase from the threshold.[3] Therefore, we take advantage of the well-established negative association between lead exposure and childhood development. In this context, an impact of higher levels of exposure among our treatment group will bias our estimates of the elevated BLL intervention toward finding no effect. However, our preferred treatment and control groups are balanced across observable characteristics and those in the treatment group do not appear to live in more risky environments as measured by prior parcel-level BLL test results. These factors alleviate concerns about a large

[1] EPA (2013) provides an extensive review of hundreds of studies investigating the effects of lead from epidemiology, toxicology, public health, nueroscience, and other medical disciplines. Effects are found across different measures of cognition and academic performance, such as IQ tests (Schnaas et al. 2006; Lanphear et al. 2005; Ris et al. 2004; Canfield et al. 2003; Bellinger, Stiles, and Needleman 1992), primary school assessments (Aizer et al. 2018; Rau, Reyes, and Urzúa 2015; McLaine et al. 2013; Zhang et al. 2013; Reyes 2011; Chandramouli et al. 2009; Miranda et al. 2009; Nilsson 2009; Miranda et al. 2007), high school graduation (Nilsson 2009; Fergusson, Horwood, and Lynskey 1997; Needleman et al. 1990), and even lower adult earnings (Nilsson 2009). Early life lead exposure also impacts externalizing behaviors such as attention, impulsivity, and hyperactivity in young children (Froehlich et al. 2009; Chen et al. 2007); increased delinquent and antisocial activity and higher rates of arrest (Aizer and Currie 2017; Reyes 2015; Wright et al. 2008; Fergusson, Boden, and Horwood 2008; Needleman et al. 2002; Dietrich et al. 2001; Needleman et al. 1996).

[2] Charlotte contains the eighteenth largest school district and is representative of other large urban areas in the United States.

[3] We present results from several different regression discontinuity designs and provide plots of outcomes by BLL values in the online Appendix.

understatement of the intervention benefits in our sample caused by any higher risks of exposure among the treatment-eligible individuals.[4]

All cases with two BLL tests exceeding the alert threshold (10 μg/dL) trigger eligibility for an intervention that includes the following actions: education for caregivers (which includes nutritional advice and information about reducing exposure in the home), a voluntary home environment investigation, and a referral to lead remediation services. A more intensive intervention can be triggered by tests over 15 μg/dL or 20 μg/dL. In addition to educating caregivers and providing a referral to remediation services, the intensive intervention typically includes: a mandatory home environment investigation; nutritional assessment; medical evaluation; developmental assessment; and a referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC).

We estimate a substantial decrease in antisocial behavior among individuals whose BLL test results trigger eligibility for an intervention. Relative to our control group, we find a 0.184 standard deviation decrease in antisocial behavior for adolescents using a summary index. We also estimate a marginally significant 0.117 increase in primary and middle school educational performance among children eligible for an intervention that is administered prior to school entry.[5] These intention-to-treat estimates are large in magnitude.[6] In fact, our results suggest that the effects of high levels of exposure on antisocial behavior can largely be reversed by the intervention—children who test twice over the alert threshold exhibit similar outcomes as children with lower levels of exposure (BLL < 5 μg/dL).

Our study offers two primary contributions. First, we provide novel estimates of the long-term impact of the standard public health response to elevated BLLs among young children in the United States. Since the CDC lowered the alert threshold to 10 μg/dL and published new recommendations in 1991, millions of children in the United States would have been eligible for the early life health and environmental treatments following results of elevated blood lead levels in states that follow the CDC recommended response.[7] Despite this large-scale public health response to lead-poisoned children, no previous studies evaluate whether there are long-term behavioral or educational benefits associated with these environmental and health interventions.

[4] Similarities between our treatment and control groups may not be that surprising given well-known issues with blood lead tests in accurately measuring exposure risk (ATSDR 2007, Kemper et al. 2005, CDC 1997). First, blood tests are better suited to detect contemporaneous shocks rather than cumulative exposure because lead has a short half-life (approx. 30 days) in the blood stream. Second, blood is often drawn through a capillary (finger-prick) sample which carries a high risk of contamination.

[5] For educational and behavioral outcomes, we pool a large set of primary outcomes into two summary indexes to limit multiple hypothesis testing concerns previously identified among evaluations of early life interventions (Anderson 2008).

[6] We estimate the effects of intervention eligibility (intention-to-treat effects) because we do not have information on intervention compliance.

[7] Since the CDC began collecting national statistics on blood lead surveillance in 1997, nearly one million children were confirmed to have elevated BLLs (BLL > 10 μg/dL) (surveillance statistics obtained from http://www.cdc.gov/nceh/lead/data/national.htm, accessed January 24, 2015). Projecting these testing rates and results back to 1991 and assuming that states follow the CDC recommended procedures implies millions of confirmed elevated BLL cases that trigger intervention. While millions may have been eligible, we do not have information on compliance rates with interventions in North Carolina or in other states.

Second, this paper contributes to a growing literature evaluating the causal impact of early childhood health interventions on long-term cognitive and behavioral outcomes (Cunha and Heckman 2008, and Currie and Almond 2011). Recent research suggests that early health and education interventions can yield large long-term benefits.[8] The Carolina Abecedarian Project—which provided a package of treatments focused on social, emotional, and cognitive development to disadvantaged children from birth through age five—has been associated with increases in educational attainment, reductions in criminal activity, and improved adult health (Barnett and Masse 2007, Anderson 2008, Campbell et al. 2014). Many other early life interventions have also proven effective, such as those administering increased medical care at birth (Bharadwaj, Løken, and Neilson 2013); nutritional supplementation for pregnant women and young children (Hoynes, Page, and Stevens 2011); nurse home visit programs (Olds et al. 1999, 2007); and high-quality preschool programs, such as Perry Preschool and Head Start (Currie and Almond 2011; Heckman, Pinto, and Savelyev 2013; Bitler, Hoynes, and Domina 2014; Conti, Heckman, and Pinto 2016). The elevated BLL intervention is unique to this literature because it has been widely applied as a public health response to an environmental toxin.

The primary goal of intervention following a confirmed elevated blood lead level is to prevent further exposure and to reduce lead levels in affected children. Two primary channels emerge through which intervention affects antisocial behavior and cognitive outcomes. First, intervention may dramatically reduce the amount of continued childhood exposure to the dangerous neurotoxin by directly reducing exposure risks within the home environment.[9] Second, long-term benefits may occur through improvements in early life health unrelated to any changes in lead exposure.[10] We cannot separately identify these two mechanisms or estimate the effects of specific elements of these elevated BLL intervention packages.[11] However, we do present evidence suggesting that both mechanisms contribute to long-term benefits. We find that households in our treatment group that are more likely to have reduced exposure, such as those with children who experience an immediate and sharp decline in post-intervention BLL test results, experience larger benefits. On the other hand, we estimate large effects for individuals eligible for treatments not

[8] See Currie and Almond (2011) for a recent review.

[9] Benefits from reductions in environmental lead levels are expected given several recent studies showing evidence of a causal relationship between exposure and long-term outcomes (Aizer and Currie 2017; Reyes 2015; Clay, Troesken, and Haines 2014; Grønqvist, Nilsson, and Robling 2014; Rau, Reyes, and Urzúa 2015; Ferrie, Rolf, and Troesken 2012; Reyes 2011; Nilsson 2009; Troesken 2008; Reyes 2007).

[10] The elevated BLL intervention package includes treatments previously demonstrated to impact later life outcomes, such as visits from health workers; increased medical care; nutritional assessments and dietary modifications; and referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). Prior research documents long-term benefits from programs similar to each of these elements: increased medical care at birth (such as those triggered by Very Low Birth Weight evaluated by Bharadwaj, Løken, and Neilson 2013); increased access to medical professionals (e.g., the Nurse-Family Partnership evaluated by Olds et al. 2007); improved early life nutrition and increased access to public assistance programs (Hoynes, Page, and Stevens 2011; Hoynes, Schanzenbach, and Almond 2016); high-quality early childcare and preschool programs which focus on these social and cognitive developmental processes (e.g., Abecedarian, Perry Preschool, and Head Start).

[11] The majority of evaluations of other early life interventions also estimate effects for an invervention package containing several components. For example, the original Abecedarian intervention combined early education with a nutritional and health component (Campbell et al. 2014); Bharadwaj, Løken, and Neilson (2013) find long-term effects from a "bundle of medical interventions" triggered by a very low birth weight threshold.

directly addressing exposure risk, suggesting that long-term benefits should be at least partially attributed to general improvements in early-childhood health.

While further research is needed to investigate the mechanisms by which individuals benefit from elevated BLL interventions, cognitive and behavioral effects associated with the standard intervention package are still relevant in evaluating current public health policy. Public health organizations now state that no BLL should be considered "safe" and have recommended lowering the threshold to identify additional children at risk for health and developmental problems caused by exposure to lead (Budtz-Jørgensen et al. 2013; CDC 2012).[12] Applying similar interventions at lower BLL thresholds may yield a large return on investment considering the magnitude of our estimates and the large returns previously associated with other early childhood interventions.[13]

The remainder of the paper is structured as follows: Section I describes the early life interventions triggered by elevated BLLs in Charlotte, NC. Section II describes our data and characterizes our intervention and control groups with summary statistics. Section III outlines our empirical strategy to identify causal effects of intervention. Section IV presents and discusses estimated effects on a variety of educational and behavioral outcomes, and Section V investigates the mechanisms driving our main results. Finally, Section VI provides a simple cost-benefit analysis and Section VII provides some concluding remarks. An online Appendix contains detailed descriptions of data sources and includes additional analysis.

I. Description of Public Health Interventions Triggered by Elevated Blood Lead Levels

The US Center for Disease Control and Prevention (CDC) currently funds the development of state and local childhood lead poisoning prevention programs and surveillance activities with the following objectives: to screen infants and children for elevated blood lead levels; to refer lead-poisoned infants and children to medical and environmental interventions; to educate healthcare providers about childhood lead poising; and to implement preventative measures to reduce childhood exposure (Meyer et al. 2003). In 1991, the CDC defined a blood lead level of 10 $\mu g/dL$ as the "level of concern" and recommended the provision of specific medical and environmental services from public health agencies following blood lead tests exceeding this threshold (CDC 1991).[14]

The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch bases intervention policies and procedures on CDC recommendations.[15] The standard experience of a child that may be at risk for lead

[12] The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch currently provides more information about nutrition and key sources of exposure for children testing over 5 $\mu g/dL$.

[13] Cost benefit analyses of early life intervention programs find a four to one return for Abecedarian (Masse and Barnett 2002) and a seven to one return associated with Perry Preschool (Karoly et al. 1998).

[14] The intervention level was 25 $\mu g/dL$ between 1985 and 1991; 30 $\mu g/dL$ between 1975 and 1985; and 40 $\mu g/dL$ between 1970 and 1975 (CDC 1991).

[15] The state of North Carolina recommends blood lead tests for all children at age 12 months and again at age 24 months. In practice, the children screened for lead is limited to those individuals who live in neighborhoods with older homes (pre-1978) and when a child's parents answer "yes" or "don't know" to any questions on the CDC lead

exposure is through an initial BLL test as part of a regular scheduled doctor's visit between the ages of one and two. In our data, we see a large number of visits clustered around 12, 18, and 24 months of age consistent with this experience. The timing of confirmatory testing is recommended to occur within one month for BLL values $> 20\ \mu g/dL$, and a typical patient usually returns to the same health provider as the initial test and gets re-tested about four months later.

If an initial test indicates a blood lead level greater than 10 $\mu g/dL$, a confirmation test is required within 6 months.[16] If a second consecutive test indicates a blood lead level greater than 10 $\mu g/dL$, a set of interventions is implemented based on the level of lead detected.[17] Figure 1 documents CDC recommendations as of 2002. Based on conversations with health workers in Mecklenburg County, NC, these CDC recommendations constituted public health policy in Charlotte back to 1991.[18]

The set of interventions for our entire sample of children with two consecutive tests over 10 $\mu g/dL$ include the following: provision of nutritional and environmental information, a referral to WIC for families not already participating, an environmental history interview to identify sources of lead, and a referral to remediation programs for cases identified as high lead risk in the home. Tests over 15 $\mu g/dL$ or 20 $\mu g/dL$ can initiate a more intensive intervention in which children also receive the following treatments: a mandatory home environmental investigation, a medical evaluation, and a detailed nutritional assessment. We test for heterogeneous intervention effects for children with BLLs over these thresholds. According to conversations with individuals from the NC Childhood Lead Poisoning Prevention Program, interventions are only substantially different at the 20 $\mu g/dL$ threshold in practice. This increase in intensity of intervention at the 20 $\mu g/dL$ threshold is evident in Figure 1, which emphasizes more direct medical and remediation action and is also supported by our estimates.

The formal protocol for the standard intervention includes first taking a medical history regarding any symptoms or developmental problems along with previous blood lead measurements and family history of lead poisoning. The healthcare provider then performs an environmental history interview during which family members are asked about the age, condition, and ongoing remodeling or repainting of a child's primary residence, as well as other places where the child spends time (including secondary homes and childcare centers). The healthcare provider then

risk exposure questionnaire. The state of North Carolina also requires lead testing for individuals participating in the Medicaid or WIC programs.

[16] Confirmatory tests after six months are not valid and thus considered a second initial test by the state.

[17] The initial test is usually based on capillary specimens typically obtained by the a finger prick where the recommended procedure for a follow-up test is through venous blood draw, which is less likely to be contaminated. Surprisingly, the blood lead surveillance data indicate that approximately one-third of follow-up tests are venous during our sample period. The lack of compliance with this aspect of the CDC recommendations is potentially due to local health workers preferring the less-invasive capillary specimen method. We find no systematic differences across the treatment and control in the type of the confirmatory test and find that the initial lead value is not predictive of the second test type. These results indicate that the variation in confirmatory test type is likely due to resources available at the testing clinics and local health worker preferences.

[18] We have found no evidence of any changes in policy preceding 2002, when the CDC recommendations were published in the NC Childhood Lead Poisoning Prevention Program lead testing manual. Since the mid-2000s, procedures have changed slightly to include the provision of nutritional and environmental information for individuals testing over 5 $\mu g/dL$. However, during the time period when our sample was tested for lead (1990–2000), the 5 $\mu g/dL$ threshold did not trigger any policy interventions.

Interpretation of Screening Test Results and Recommended Follow-up

Blood Lead Level (μg/dL)	Comments
<10	A child with this Blood Lead Level (BLL) is not considered to have an elevated level of exposure. Reassess or rescreen in one year. No additional action is necessary unless exposure sources change.
10-14	The CDC considers 10 μg/dL to be a level of concern. Perform diagnostic test on venous blood within three months. If the diagnostic test is confirmatory, the child should have follow-up tests at three month intervals until the BLL is <10 μg/dL. Provide family lead education. Refer for nutrition counseling.
15-19	A child in this category should also receive a diagnostic test on venous blood within three months. If the diagnostic test is confirmatory, the child should have additional follow-up tests at three month intervals. Children with this level of exposure should receive clinical management. Parental education and nutritional counseling should be conducted. A detailed environmental history should be taken to identify any obvious sources of lead exposure.
20-44	A child with a BLL in this range should receive a confirmatory venous test within one week to one month. The higher the screening test, the more urgent the need for a diagnostic test. If the diagnostic test is confirmatory, coordination of care and clinical management should be provided. An abdominal x-ray is completed if particulate lead ingestion is suspected. Nutrition and education interventions, a medical evaluation, and frequent retesting (every 3 months) should be conducted. Environmental investigation and lead hazard control is needed for these children.
45-69	A child in this category should receive a confirmatory venous test within 48 hours. If the screening blood lead level is between 60-69 μg/dL, the child should have a venous blood lead level within 24 hours. If confirmatory, case management and clinical management should begin within 48 hours. Environmental investigation and lead hazard control should begin as soon as possible. A child in this exposure category will require chelation therapy and an abdominal x-ray is completed if particulate lead ingestion is suspected.
≥70	A child with a BLL ≥70 requires immediate hospitalization as lead poisoning at this level is a medical emergency. Confirmatory venous testing should be done as soon as possible. An abdominal x-ray is completed if particulate lead ingestion is suspected and chelation therapy should begin immediately. Case and clinical management including nutrition, education, medical and environmental interventions, must take place as soon as possible.

Information from Centers for Disease Control and Prevention. Screening Young Children for Lead Poisoning: Guidance for State and Local Public Health Offices. November 1997. Atlanta, Georgia. United States Department of Health and Human Services, Public Health Services, CDC, 1997 and Centers for Disease Control and Prevention. Managing Elevated Blood Lead Levels Among Children: Recommendations from the Advisory Committee on ChildhoodLead Poisoning Prevention. March 2002

Figure 1. Elevated Blood Lead Level Intervention Policy of the Children's Environmental Health Branch within the North Carolina Department of Health

Notes: This guide represents North Carolina Health Department Policies in 2002 (entirely based on CDC recommendations). Since some of our sample is tested prior to 2002, we have investigated and found no changes in lead policy in the years preceding. Conversations with the North Carolina Childhood Lead Poisoning Prevention Program have confirmed that these guidelines were used at least back to 1991. Based on conversations with health workers in North Carolina and specifically Mecklenburg County, NC, along with inspection of the recommended interventions, the thresholds for which policy is substantially different is the 10 μg/dL and the 20 μg/dL threshold. We add emphasis of interventions triggered by underlining the intervention components (excluding further testing).

determines whether a child is being exposed to lead-based paint hazards at any or all of these places. The environmental history also includes an inquiry about other sources of potential lead exposure.[19]

Based on the environmental history interview or a confirmatory test over 20 μg/dL, a professional lead remediation team conducts a lead inspection at the child's home. This inspection leads to a determination of the home being lead-safe or in need of lead remediation. The provision of lead remediation services involves the removal of lead contaminants, which usually requires the replacement of windows and doors and the repainting of interior/exterior walls. During our sample time period, lead remediation was primarily funded through local government agencies, HUD-based lead remediation grants, nonprofits, and privately. The cost for lead remediation is not trivial with the average price of these repairs totaling $7,291.[20]

Since lead levels in the body are the result of a combination of lead exposure and the body's absorption of lead into the brain, nutrition can mitigate the effects of lead exposure. While the effectiveness of nutritional interventions is not established, research suggests that deficiencies in iron, calcium, protein, and zinc are related to BLLs and potentially increase vulnerability to negative effects of lead (CDC 1991). A nutritional assessment includes taking a diet history with a focus on the intake of iron-, vitamin C-, calcium-, and zinc-rich foods. The nutritional information is also used to assess the ingestion of non-food items as well as water sources that contain lead for the family. The healthcare provider inquires into participation in WIC or the Supplemental Nutrition Assistance Program (SNAP or "food stamp") and refers the family to these programs if they are not currently participating. For children with a confirmatory test over 20 μg/dL, a medical examination is conducted with particular attention to a child's psychosocial and language development. In cases of developmental delays, a standardized developmental screening test is recommended, which offers referrals to an appropriate agency for further assessment.

II. Data

We merge blood lead surveillance data, public school records, and criminal arrest records at the individual level for children born between 1990 and 1997 in Charlotte-Mecklenberg County, NC.[21] Blood lead surveillance data are maintained by the NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch.[22] This dataset includes BLL test results, which allow us to determine

[19] Some additional sources of lead include vinyl mini blinds manufactured prior to 1996; soil and dust, which is primarily contaminated by previous existence of lead paint; leaded gasoline or pipes; as well as toys and pottery from overseas.

[20] This estimated cost is based on cost data from LeadSafe Charlotte, which began operations in 1998 and was funded by HUD to remediate lead from homes in Charlotte.

[21] We restrict our sample to individuals born in 1997 or earlier to allow all individuals to reach age 16 by 2013.

[22] North Carolina requires all children participating in Medicaid or WIC to be screened for lead at one or two years of age. Other children are screened if a parent responds "yes" or "don't know" to any of the questions on a CDC Lead Risk Assessment Questionnaire. The North Carolina Blood Lead Surveillance Group estimates that it screened between 21.9 and 30.4 percent of children one and two years of age from 1995 through 1998, and we expect screening rates were similar during our analysis period (Miranda et al. 2007).

which children were eligible for various lead policy interventions due to two tests with BLLs of 10 μg/dL or above.[23]

We match individual children who receive blood lead tests to two additional databases in order to examine the impact of elevated BLL interventions on educational and behavioral outcomes. First we match BLL test results to administrative records from Charlotte-Mecklenburg Schools (CMS) that span kindergarten through twelfth grade and the school years 1998–1999 through 2010–2011.[24] Specifically, we incorporate student demographics on race and home address, yearly end-of-grade (EOG) test scores for grades three through eight in math and reading,[25] number of days absent, days suspended from school, and the number of incidents of school crime.[26]

To examine adult criminal outcomes, we match our lead database to a registry of all-adult (defined in North Carolina as age 16 and above) arrests in Mecklenburg County from 2006 to 2013.[27] The arrest data include information on the number and nature of charges as well as the date of arrest. These data allow us to observe adult criminality regardless of whether a child later transferred or dropped out of school, the main limitation is that it only includes crimes committed within Mecklenburg County. While we cannot observe whether individuals are more or less likely to leave Mecklenburg County following school, we do not find any statistically significant difference in the probability of attending public high school in the county, which alleviates any concerns about differential attrition/mobility between our treatment and control groups.[28]

We draw on two additional databases to control for parental and housing factors, which may influence outcomes. The first data are the population of birth certificate records from the state of North Carolina from 1990–1997 from which we obtain birth weight and years of parental education.[29] The second database is county assessor's data for all parcels. Property data can be matched to lead test results based on home address. We augment this parcel data with building permits for all home renovations between 1995 and 2012. This database allows us to incorporate information on housing stock and neighborhoods, directly accounting for some degree of home maintenance that may be correlated with lead exposure. This database on parcels allows us to generate variables for prior home renovations, age, and type of housing

[23] These data also include a child's name, gender, birth date, test date, BLL, and home address.

[24] We are able to match 74 percent of individuals with two tests and one test > 10 μg/dL in the blood lead surveillance data to a student record in CMS. We do not find any statistically significant differences in the ability to match blood lead test data to CMS school records (which is required for an individual to be included in our estimation sample) and report a match rate comparison in the online Appendix (Table A5).

[25] Test scores are standardized at the state level by grade and year.

[26] According to NC State Statute 115C 288(g), any incident at school involving any violent or threats of violent behavior, property damage, theft or drug possession must officially be reported to the NC school crimes division. This statute ensures that this measure of school crime is consistently reported across schools and cannot be treated differently based on school administrators.

[27] We use first name, last name and date of birth to link individuals across the two data sources. Details are provided in the Appendix.

[28] These results are presented in the online Appendix (Table A5).

[29] We are able to match approximately 54 percent of birth records to our lead database. We do not limit our estimation sample by a match to this database; we create indicator variables for any individuals we are unable to match to the birth record database. Even though this match rate is somewhat lower than our other databases, the variables from this database are simply used as control variables, and we later show that this match rate is unrelated to our lead policy intervention group.

Table 1—Means of Demographic, Housing, and Neighborhood Characteristics

	Intervention	Control	Difference
Background characteristics			
Male	0.61	0.58	0.02
	(0.49)	(0.49)	(0.06)
Minority	0.77	0.77	−0.00
	(0.42)	(0.42)	(0.05)
Stand-alone residence	0.58	0.57	−0.00
	(0.50)	(0.50)	(0.06)
Home built pre-1978	0.79	0.78	−0.01
	(0.41)	(0.42)	(0.05)
Past lead tests at a home (mean μg/dL)	4.40	4.52	−0.12
	(1.16)	(1.51)	(0.25)
Age at blood lead test (months)	28.07	25.57	2.50
	(17.21)	(14.15)	(1.82)
Mother education (years)	11.92	11.45	0.47
	(2.96)	(2.28)	(0.37)
Birth weight (ozs)	115.09	110.90	4.19
	(20.37)	(21.57)	(3.05)
Index of neighborhood attributes	−0.48	−0.58	0.10
	(0.88)	(0.89)	(0.10)
F-stat (p-value)			0.237
Observations	119	182	301

Notes: This table reports means and standard deviations for the group eligible for intervention (two tests $\geq$ 10 μg/dL) and our control group (first test $\geq$ 10 μg/dL, second test $\geq$ 5 but $<$ 10 μg/dL), as well as the mean difference and the standard error of the difference. The number of observations by intervention and control groups for each variable is reported at the bottom with the exception of the following variables: *Stand-alone residence* (*99/143*)*; Built pre-1978* (*108/148*)*; Past Lead Tests at a Home* (*49/87*)*; Mother education* (*76/131*)*; Birth weight* (*76/131*). The *Index of neighborhood attributes* is an index measure of disadvantage derived from census block group variables (based on address at first lead test). We calculate this summary measure from an unweighted z-score sum of the percent of households in a 2000 Census Block Group (CBG) without a high school graduate, the CBG poverty rate, the CBG fraction of single female headed households, and the CBG population density. The p-value from a F-test of joint significance of all of the background characteristics is also reported. Results from the balance test specification are presented in the online Appendix (Table A4).

structure.[30] We match our sample to these two datasets but do not require a match for a observation to be included in our estimation sample. Instead, we create dichotomous variables indicating a non-match across the birth record and parcel databases and assigned missing variables a value of zero.[31]

Tables 1 and 2 display summary statistics for our intervention group and control group (defined in Section III) after merging all data and limiting our analysis to individuals born prior to 1998.[32] Individual attributes are similar between the two groups

[30] The lead database is matched to parcel records 86 percent of the time with differences primarily a result of incomplete home address information.

[31] We also do not find significant differences in whether we are able to match individuals in our estimation sample to the birth record or parcel information databases and report this comparison in the online Appendix (Table A5).

[32] We provide a table describing all variables used and their sources in the online Appendix (Table A1). We also present summary statistics for the entire population after merging all data (online Appendix Tables A2 and A3). In

TABLE 2—MEANS OF EDUCATION AND BEHAVIOR OUTCOMES

	Intervention	Control	Difference
Blood lead level at initial test (μg/dL)	17.85	12.09	5.76
	(8.25)	(4.41)	(0.73)
Education index	0.08	−0.05	0.13
	(0.60)	(0.71)	(0.08)
Reading test score (average 3rd–5th grade)	−0.44	−0.58	0.14
	(0.83)	(0.91)	(0.12)
Math test score (average 3rd–5th grade)	−0.46	−0.53	0.07
	(0.81)	(0.96)	(0.12)
Repeat a grade (grades 1–5)	0.15	0.14	0.01
	(0.36)	(0.35)	(0.04)
Reading test score (average 6th–8th grade)	−0.32	−0.50	0.18
	(0.81)	(0.95)	(0.12)
Math test score (average 6th–8th grade)	−0.31	−0.43	0.12
	(0.82)	(0.88)	(0.11)
Repeat a grade (grades 6–9)	0.14	0.21	−0.07
	(0.35)	(0.41)	(0.05)
Adolescent antisocial behavior index	−0.15	0.10	−0.25
	(0.47)	(0.83)	(0.08)
Days suspended (6th–10th grade)	9.25	17.67	−8.42
	(15.80)	(32.44)	(3.20)
Days absent (6th–10th grade)	30.61	45.65	−15.05
	(36.31)	(54.71)	(5.70)
School reported crimes (6th–10th grade)	1.97	3.45	−1.47
	(3.40)	(6.75)	(0.67)
Ever arrested	0.08	0.18	−0.10
	(0.27)	(0.38)	(0.04)
Ever arrested—violent	0.03	0.12	−0.09
	(0.16)	(0.32)	(0.03)
Ever arrested—property	0.04	0.07	−0.03
	(0.20)	(0.26)	(0.03)
Observations	119	182	301

Notes: This table reports means and standard deviations of blood lead levels and outcome variables for the group eligible for intervention (two tests ≥ 10 μg/dL) and our control group (first test ≥ 10 μg/dL, second test ≥ 5 but < 10 μg/dL), as well as the mean difference between the two groups along with the standard error of the difference. We follow the methodology in to create a summary index (a weighted mean of standardized outcomes). The education index includes third through fifth grade math and reading test score results and grade retention between third and ninth grade. All test scores are standardized based on state-wide averages by grade and calendar year. The antisocial behavior index includes measures of number of days suspended and absences (sixth through tenth grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

in our estimation sample (Table 1), yet the intervention group has substantially better education and behavioral outcomes (Table 2). We further explore these differences through a regression analysis discussed in the following section.

general, we observe lower educational and behavioral outcomes for children who receive a blood lead test compared to untested children and worse outcomes for those with high detected BLLs relative to those with miminal BLLs. Lead tests and higher test results are more likely among children living in older homes, lower income neighborhoods, and with less parental education.

III. Empirical Framework

In order to assess the impact of the early life interventions triggered by elevated BLLs, we estimate the following model for all individuals who have an initial BLL test above 10 μg/dL, return for a second test, and can be matched to CMS public school records:

$$Y_i = \alpha Intervention_i + \mathbf{X}_i \beta + \epsilon_i, \tag{1}$$

where Y_i is an outcome for individual i and $\mathbf{X}_i$ includes a wide range of controls.[33] Each outcome is regressed on an indicator, $Intervention_i$, for whether child i received two consecutive tests over the intervention threshold of 10 μg/dL. Since the presence of lead paint is heavily concentrated in older residential neighborhoods, standard errors are clustered at the Census Block Group (CBG) level.[34]

Our primary results focus on intervention effects for two summary index outcomes: educational performance and adolescent antisocial behavior. We follow the methodology for creating a summary index as outlined in Anderson (2008) in a re-evaluation of several early childhood intervention programs.[35] Besides dealing with concerns about multiple hypothesis testing, a summary index can be potentially more powerful than individual-level tests due to random error in outcome measures. The antisocial behavior index includes measures of absences and number of days suspended (sixth through tenth grade), school reported crimes, and adolescent criminal arrests from the age of 16 through 18.[36] The educational performance index includes third through eighth grade math and reading test score results as well as grade retention between first and ninth grade.[37] We also estimate and present results separately for individual outcomes used in the summary indexes.

Throughout the empirical analysis, we estimate equation (1) restricting our sample to individuals with an initial BLL test of 10 μg/dL or greater. Our primary control group includes individuals who have one test over the alert threshold of 10 μg/dL and the confirmatory test within six months between 5 and 9 μg/dL. Figure 2 illustrates the various combinations of BLL values among all individuals

[33] We include indicators for gender, race/ethnicity, birth year, single family home and home built pre-1978 as well as continuous variables for age at blood test, birth weight, parental education level, the average previous lead test results associated with the residential address listed, as well as an index measure of disadvantage derived from census block group variables (based on address at first lead test). We calculate this summary neighborhood measure from an unweighted z-score sum of the percent of households without a high school graduate, the CBG poverty rate, the fraction of single female headed households, and the CBG population density.

[34] There are 151 CBGs in our primary analysis. Given the downward bias detected when the number of observations differs across groups or for other forms of cluster heterogeneity in Carter, Schnepel, and Steigerwald (2017), we also calculate the *effective number of clusters* around 30 for our regressions. This level is not associated with substantial bias in Carter, Schnepel, and Steigerwald (2017).

[35] The steps to calculate the summary index are outlined in detail in Anderson (2008). We also provide a description of the steps in the online Appendix.

[36] We treat the absences as coming from truancy, a behavioral outcome, but note that absences could also be due to health problems.

[37] We limit our analysis to school outcomes through tenth grade because our public school records are available only through the 2010–2011 school year and we have very few cohorts in eleventh or twelfth grade by 2010. Criminal arrest data is available for an additional 2.5 years (through 2013) allowing us to measure arrests between 16 and 18 years of age for many of the children receiving lead tests since 1992.

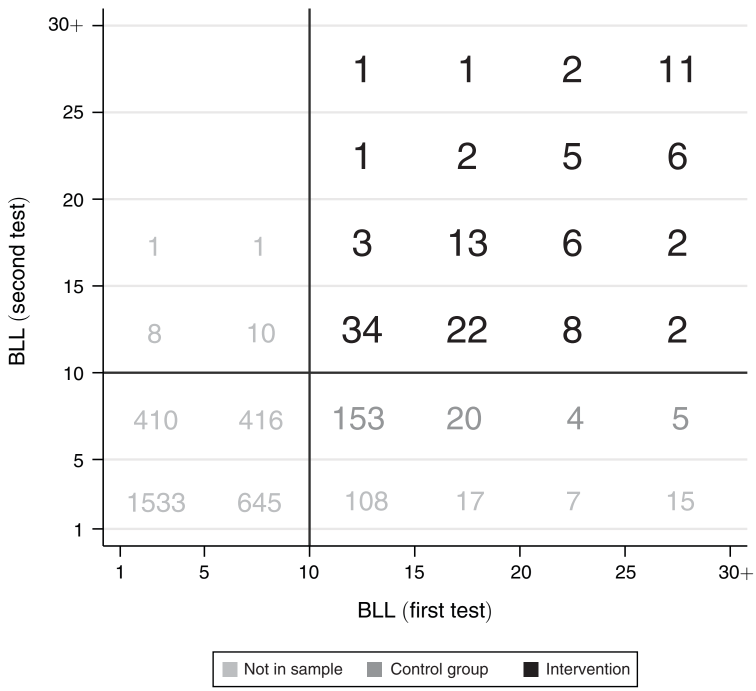

Figure 2. Observations by First and Second BLL Test

Notes: This figure provides a grid with first and second BLL test result values indicating treatment and control regions and highlights the variation in BLL between the first and second BLL test as well as the number of observations in our estimation sample for various combinations of first and second BLL test results.

with at least two tests with the larger font numbers highlighting the individuals that populate our treatment and control groups.[38]

Our identification strategy relies on the fact that our treatment and control groups both receive a BLL test with an elevated initial value and follow-up public health recommendations for re-testing BLL. This criteria should address most issues of selection on testing as well as parental and environmental differences that may impact the ability or desire to re-test. Since the test results are, on average, higher for those eligible for the intervention package, this group may experience a more dangerous level of underlying lead exposure which, based on previous literature, is associated with larger education and behavioral deficits. Figures 3 and 4 clearly depict more negative outcomes for reading/math test scores, repeat grades in school, suspensions, absences, and crime associated with higher BLL values.[39]

To assess whether intervention is unrelated to unobserved determinants of cognitive and behavioral outcomes, we compare observable characteristics (including

[38] We plot the distribution of BLL values for all first and second test values in the online Appendix (Figure A8).

[39] In the online Appendix, Table A2 presents a similar pattern for the full population of CMS students with BLL tests born between 1990 and 1997.

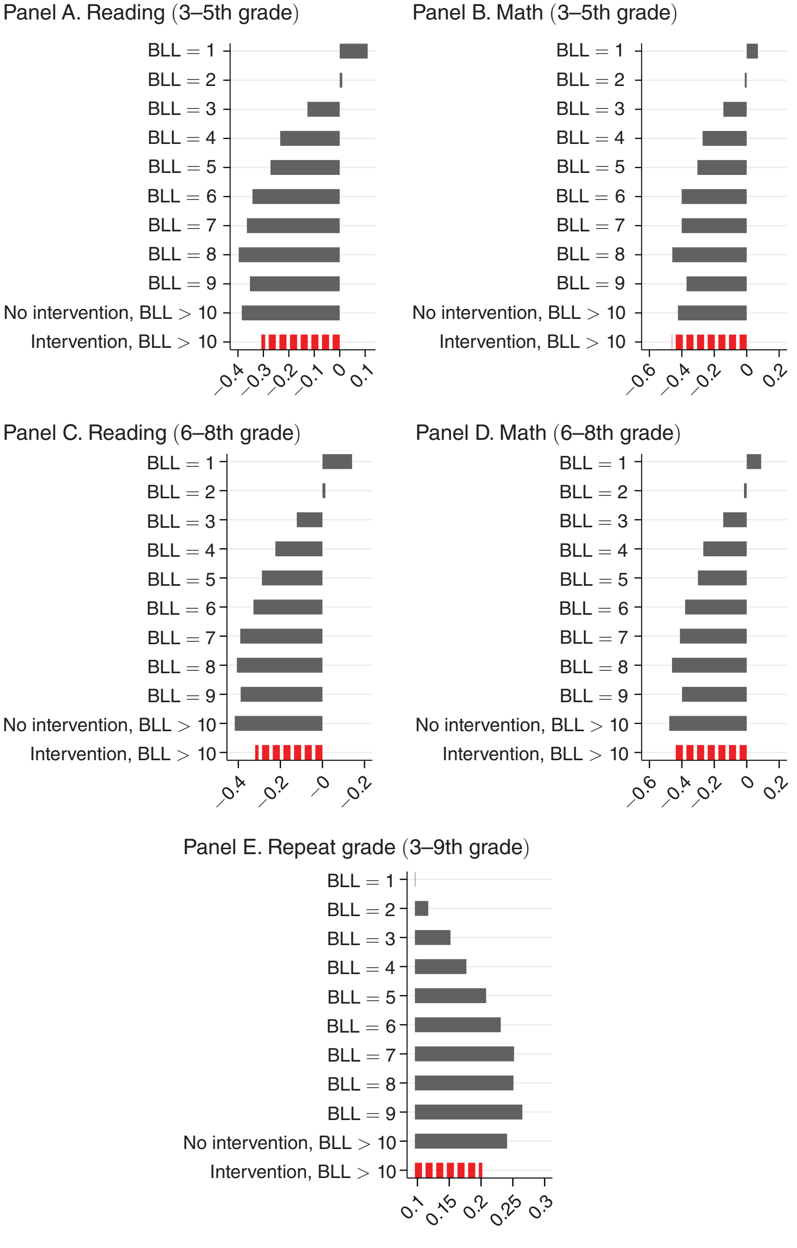

FIGURE 3. AVERAGE EDUCATION OUTCOMES BY BLOOD LEAD LEVEL

Notes: This figure depicts mean outcomes by the level of initial BLL test result for each of the education outcomes. The group "No intervention, BLL > 10" includes any individual with an initial test over 10 μg/dL but without a second test over 10 μg/dL. This group includes our control group (first test > 10, second test > 5 but < 10) as well as other individuals with at least one BLL test > 10 but not in our intervention group. Means for our control group are, in general, worse off compared to this group and are listed in Table 2. The "intervention, BLL > 10" group represents the treatment group in our estimation sample—those who are eligible for the intervention following two consecutive tests over the threshold of 10 μg/dL.

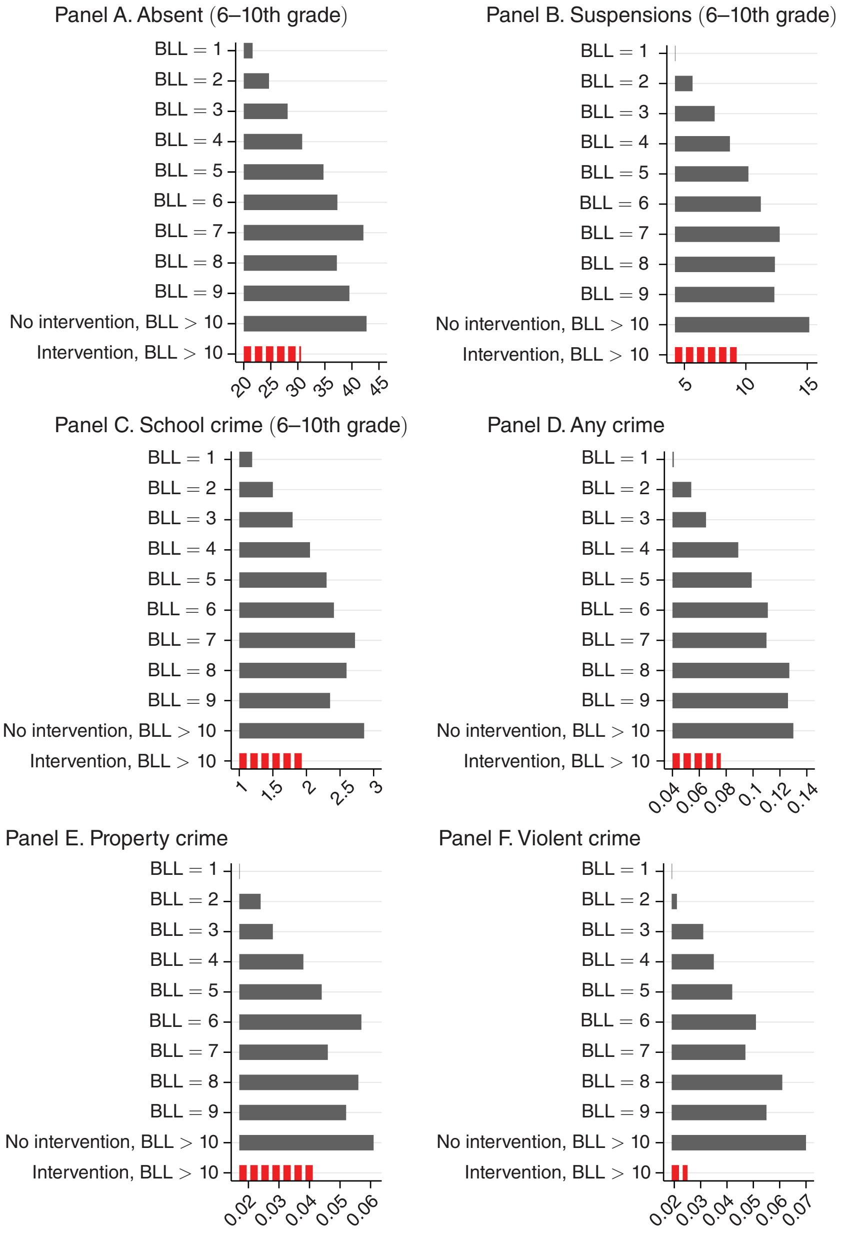

FIGURE 4. AVERAGE EDUCATION OUTCOMES BY BLOOD LEAD LEVEL

Notes: This figure depicts mean outcomes by the level of initial BLL test result for each of the the behavioral outcomes. The group "No intervention, BLL>10" includes any individual with an initial test over 10 μg/dL but without a second test over 10 μg/dL. This group includes our control group (first test >10, second test >5 but <10) as well as other individuals with at least one BLL test >10 but not in our intervention group. Means for our control group are, in general, worse off compared to this group and are listed in Table 2. The "Intervention, BLL>10" group represents the treatment group in our estimation sample/those who are eligible for the intervention following two consecutive tests over the threshold of 10 μg/dL.

measures of parental quality, health at birth, housing quality, and neighborhood quality) across the intervention and control groups. Despite large and statistically significant differences between mean outcomes in Table 2, we find no significant differences among observable characteristics between our intervention and control groups in Table 1. The small differences in individual attributes between the intervention and control group is formally investigated in a balance test presented on the bottom of Table 1—we cannot reject that all variables are jointly equal to zero.[40] Notably, we do not find a statistically significant difference in prior BLLs tied to the parcel addresses of our treatment and control groups, suggesting that exposure risks are similar across the two groups.[41] This result points toward measurement error as an important source of variation in treatment eligibility within our estimation sample.[42]

Throughout our analysis we refer to our estimates as intervention effects, but our estimated effects represent a combination of several responses to intervention. First, since we do not directly observe participation in any intervention programs, our estimated effects are intention-to-treat (or "ITT") treatment effects, which represent a combination of the direct impact of intervention on outcomes and the probability of compliance with the intervention.[43] Second, the estimated impact includes the role of parental or other inputs that react to a confirmed elevated BLL. For example, intervention could directly impact child nutrition and the level of lead in the home environment but also impact the amount of care and attention provided by a parent. While decomposing the various components of this total effect would be extremely useful in designing early childhood intervention programs, our estimated intervention effect is more relevant for the evaluation of the CDC-recommended public health response to elevated BLLs. The effect of the policy will always include direct benefits of intervention, potential noncompliance, and any indirect benefits from family or community responses to intervention.

IV. Results

After a second test confirms an elevated BLL, the NC Department of Health requires the implementation of the interventions recommended by the CDC (as listed in Figure 1). The CDC recommends testing until an individual with elevated levels tests below the alert threshold of 10 μg/dL. To assess whether individuals comply with intervention after an elevated BLL is confirmed, we estimate the effect of intervention on several measures of continued testing. Columns 1 through 3 of Table 3 demonstrate that compared with the control groups, those with confirmed

[40] Results from the balance test specification are presented in the online Appendix (Table A4).

[41] We also compare outcomes across those living in the same parcels *prior* to the children in our estimation sample using the same empirical specification (equation 1) and report these results in Table 6. Despite our treatment group having higher detected BLLs, we do not find evidence from these specifications that these higher BLLs are driven by differences in the home environment.

[42] Blood testing is a noisy measure of exposure for two reasons: (i) a short half-life of lead in blood (30 days) and (ii) a high risk of contamination during testing procedures that utilize capillary sampling (ATSDR 2007; Kemper et al. 2005; CDC 1997).

[43] It is possible that some families refuse any intervention after two consecutive tests over the alert threshold. These families would be "treated" in our framework since we do not observe implementation.

Table 3—Do Individuals Comply with the Elevated BLL Intervention?

	3rd test 100 days	Recieved 3rd test	Total number of tests	Months between tests 2 and 3	Future remediation
	(1)	(2)	(3)	(4)	(5)
Intervention	0.438	0.524	2.661	−7.563	0.048
	(0.045)	(0.045)	(0.318)	(1.363)	(0.032)
Mean (control)	0.08	0.23	2.35	12.22	0.03
Observations	301	301	301	113	301

Notes: This table presents results for specifications with dependent variables assessing whether individuals eligible for an intervention appear to comply with the recommended procedures including whether they show up for the follow-up test following the second confirmatory test within 100 days, whether they ever show up for a third test, the total number of BLL tests, the timing between the follow up tests, and whether the property is remediated following a referral to the LeadSafe Charlotte remediation program. All regressions include the full set of control variables listed in the table notes of Table 4. There are fewer observations for column (4) due to the limited number of individuals that have third tests.

elevated BLLs are 44 percentage points more likely to have a third test within 100 days of the confirmatory BLL test result, have twice as many overall tests, and respond quickly following a second elevated test by obtaining a third test within approximately three months. Overall, 79 percent of individuals in our intervention group continue testing until their BLL $\leq 10\ \mu\text{g}/\text{dL}$ (as depicted in Figure 5). While these results provide some confidence that, on average, interventions are administered to children who are supposed to receive them according to local health department policy, all of our estimates remain intention-to-treat estimates since we do not have data indicating participation in the components of the intervention package.

The first panel of Table 4 estimates equation (1) for our education summary indexes and for individual outcomes grouped by different grade levels. Combining math and reading test scores between the third and eighth grade as well as grade retention outcomes between the first and ninth grade into a summary index, we estimate a marginally significant 0.117 standard deviation increase in educational performance associated with the elevated BLL intervention. While the majority of our test score estimates are imprecise, they are at least consistent with benefits from intervention in direction and magnitude.

Columns 8 through 14 of Table 4 report a large and significant decline in antisocial behavior associated with elevated BLL intervention. Relative to the control group, we estimate a 0.184 standard deviation decrease in our antisocial behavior summary index associated with intervention. This represents a very large drop from the average index value of 0.10 for the control group. The pattern of estimates across individual outcomes of suspensions, absences, school crimes, and criminal arrests reported in Table 4 consistently demonstrates improvements associated with intervention.

Overall, the pattern of our estimated effects are consistent with recent work suggesting that effects from early-childhood interventions that boost non-cognitive skills do not fade out over time (Heckman, Pinto, and Savelyev 2013). The magnitude of the difference between control and treatment group outcomes grow

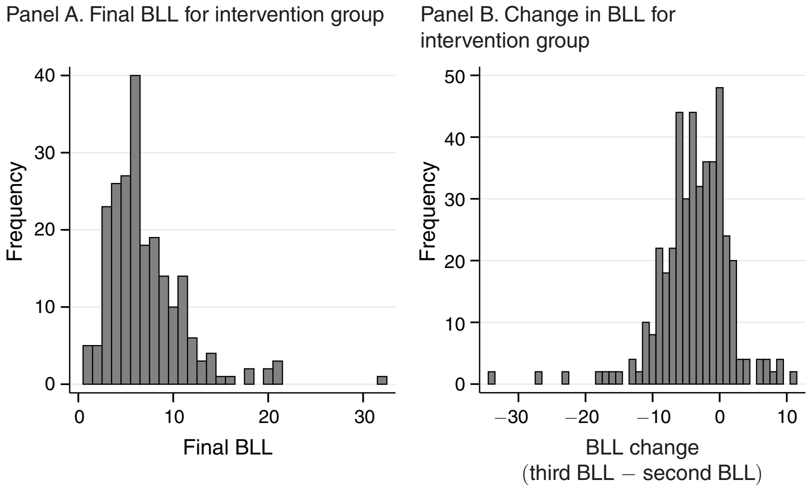

Figure 5. Change in BLLs

Note: This figure plots the distribution of observations by the final BLL value (panel A) and the net change in detected BLL between the second and third test (panel B) for the intervention group (first and second test $\geq 10\ \mu g/dL$).

Table 4—Effects of an Elevated BLL Intervention on Education and Behavioral Outcomes

	Education index (1)	Reading 3–5th (2)	Math 3–5th (3)	Repeat 1–5th (4)	Reading 6–8th (5)	Math 6–8th (6)	Repeat 6–9th (7)
Intervention	0.117	0.153	0.099	0.035	0.219	0.163	−0.036
	(0.067)	(0.119)	(0.117)	(0.039)	(0.102)	(0.102)	(0.043)
Observations	301	240	244	301	235	236	301
	Behavioral index (8)	Suspended 6–10th (9)	Absent 6–10th (10)	School crime 6–10th (11)	Arrest (12)	Arrest violent (13)	Arrest property (14)
Intervention	−0.184	−5.936	−9.786	−1.219	−0.073	−0.076	−0.017
	(0.082)	(2.698)	(4.281)	(0.607)	(0.043)	(0.027)	(0.037)
Observations	301	301	301	301	301	301	301

Notes: This table reports the estimated effects of EBLL intervention eligibility on the various educational and behavioral outcomes. The treatment and control groups as well as the outcome variables are defined in Table 2. All estimates in this table are based off of a regression specification including the following controls: indicators for gender, minority (black or hispanic), birth year, single family home, pre-1978 parcel age, missing school test scores, missing birth record, missing parcel information; and continuous controls for birth weight, age at blood test, average previous lead levels for prior households in the home, mother's years of education, and a CBG-based neighborhood index described in Table 1.

with later outcomes—we find larger effects for the later test score results compared to primary school test scores and the largest impact on secondary school behavior outcomes.

In Figure 6, we estimate treatment effects relative to six different control groups defined by a range of the average detected BLLs. Note that the control groups in

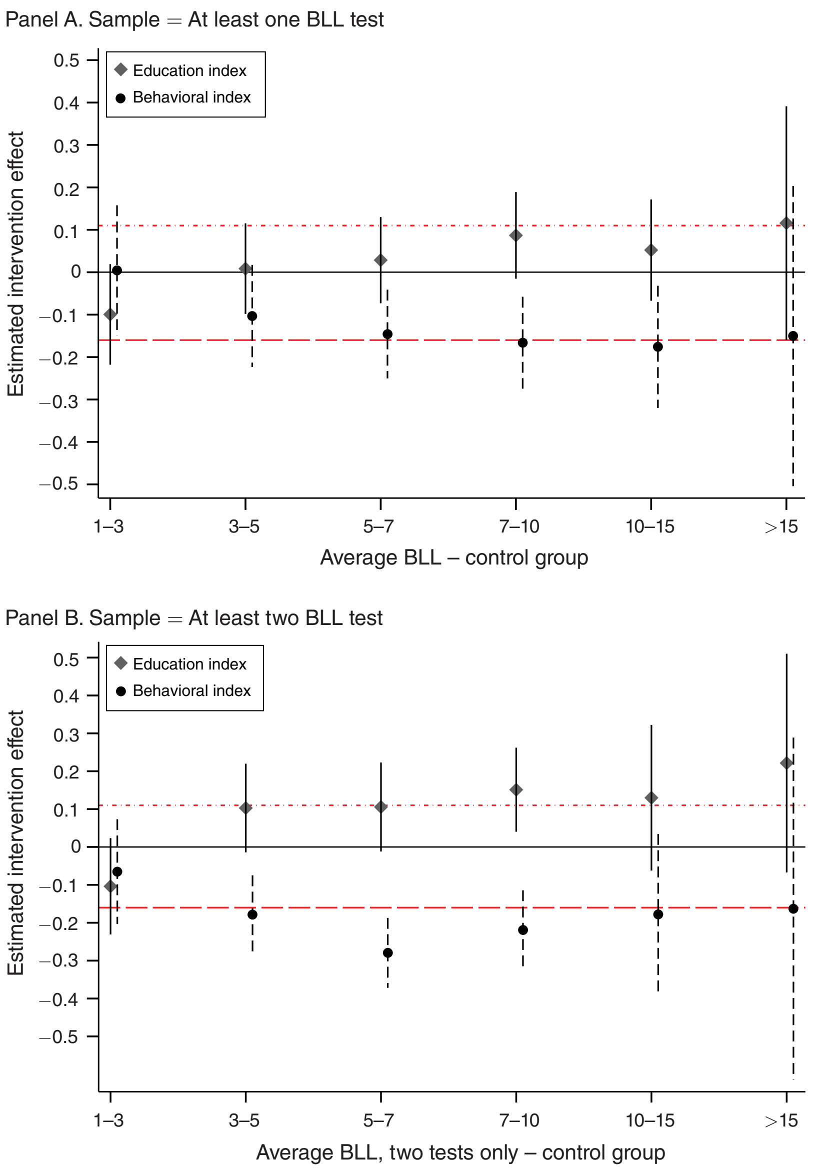

Figure 6. Estimated Treatment Effect Relative to Alternative Control Groups (*by average BLL*)

Notes: This figure plots estimates of eligibility for the intervention on the summary index outcomes comparing our treatment group (two tests with BLL 10 or more) with groups defined by their average BLL test results. These control groups are no longer restricted to having an initial BLL test above 10. Panel A includes individuals with at least one BLL test in the control group while panel B includes only those with at least two BLL tests. The sample sizes for each alternative control group indicated by the labels on the horizontal axis are as follows: panel A: Avg. BLL 1–3 (5,540); Avg. BLL 3–5 (7,959); Avg. BLL 5–7 (3,987); Avg. BLL 7–10 (2,044); Avg. BLL 10–15 (638); Avg. BLL > 15 (145); panel B: Avg. BLL 1–3 (783); Avg. BLL 3–5 (1,450); Avg. BLL 5–7 (681); Avg. BLL 7–10 (351); Avg. BLL 10–15 (72); Avg. BLL > 15 (15). All regressions include the full set of control variables listed in the table notes for Table 4.

these specifications are no longer restricted only to individuals with an initial test above 10 μg/dL. This plot accomplishes two objectives. First, the plot demonstrates that our estimated treatment effects are consistent with the idea of worse outcomes for individuals with higher BLL values since we only find sizable and significant effects when we compare our treatment group to control groups with higher BLL values (five and above). Second, the plot provides an interesting framing of our estimated treatment effects in that we do not find statistically significant differences between our intervention eligible group and children detected to have BLL levels below 5 μg/dL. We find that the elevated BLL intervention can largely mitigate the education and behavioral deficiencies associated with higher levels of exposure.

In our context, higher levels of underlying exposure among our treatment group would lead to a downward-biased estimate of the benefits from the elevated BLL policies. We provide a number of results that show limited evidence of such a downward bias. First, we do not find strong evidence of a large difference in exposure risk when comparing average BLL test results within treatment and control parcels in years prior to the testing of our treatment and control individuals (Table 2). We also do not find evidence that observable characteristics correlated with higher levels of disadvantage (e.g., low birth weight, low maternal education, high neighborhood poverty) are consistently worse among the intervention group relative to the control group.[44]

The lack of any statistical difference in demographic and parcel characteristics correlated with higher lead exposure risks suggests that, in this setting, a large part of the variation in treatment eligibility could be explained by idiosyncratic variation in measuring exposure through blood lead testing. Specifically, several characteristics of blood lead testing support measurement error as an important source of variation in test results. First, BLL levels are influenced by the relationship between date of exposure (which is usually unknown to the family) and the date of testing with only a month of passed time generating over a 50 percent decrease in the BLL due to a short half-life of lead in blood (30 days). Second, capillary sampling (a "finger-prick" method) is the most common type of test for both initial and confirmatory tests in Charlotte during our time period of analysis and is known to have a high contamination risk relative to alternative testing procedures.[45]

We present additional results in the online Appendix to assess whether our estimates are robust to alternative specifications. These exercises include: the influence on various sets of controls on estimated effects (online Appendix Table A6), specifications that include other control variables than our baseline set described in Section III (online Appendix Table A7), and estimates using regression discontinuity designs (online Appendix Table A8). Given the size of our estimation sample, estimates from the regression discontinuity specifications or those including a more

[44] We also do not find that estimated effects increase when including controls for observable characteristics (see Table A6 in the online Appendix).

[45] Other non-blood testing procedures, such as measuring lead in children's teeth, are more accurate but also more expensive and therefore less prevalent. Tooth lead testing is a more accurate measure of cumulative exposure since there is little risk for contamination and due to the fact that the elimination half-life for inorganic lead in bone is approximately 27 years (ATSDR 2007).

extensive set of controls are usually similar in direction and magnitude, but are less precise.[46]

We also evaluate whether elevated BLL intervention impacts other children in the household by matching intervention and control individuals to their siblings. Among a small number of sibling observations, we find patterns consistent with there being an effect of intervention for the household with the benefits concentrated among younger siblings (online Appendix Table A9). To the extent interventions reduce levels of dangerous lead exposure, we expect larger effects for younger siblings since older siblings would already be damaged from exposure. We interpret these results cautiously since they are based on few observations and are associated with large standard errors.

V. Mechanisms and Intensity of Treatment

The substantial improvements associated with the elevated BLL interventions likely represent a combination of direct and indirect effects from both the local health department's response and the parental response to lead exposure. Two primary channels emerge through which intervention affects antisocial behavior and cognitive outcomes. First, intervention may dramatically reduce the amount of continued exposure to the dangerous neurotoxin by directly reducing exposure risks within the home environment. Second, long-term benefits may occur through improvements in early life health unrelated to any changes in lead exposure.

As previously discussed in Section I and evident in Figure 1, higher intensity interventions are recommended following confirmatory tests over 15 μg/dL and 20 μg/dL. We explore whether these higher intensity interventions are associated with larger benefits in the first panel of Table 5. We find substantial benefits among those with a confirmatory test over 20 μg/dL and do not detect any additional benefits for those with a confirmatory test between 15 and 20 μg/dL. Additional effects at the 15 μg/dL threshold are not expected in this setting since, according to individuals at the North Carolina Childhood Lead Poisoning Prevention Program, interventions are only substantially different at the 20 μg/dL threshold in practice. These results suggest larger benefits from more intensive interventions but are based on a small number of individuals. The larger effects also do not help distinguish between mechanisms since the higher intensity intervention is associated with more targeted efforts to reduce exposure through mandatory home investigations but is also associated with an increase in medical attention, developmental surveillance, and access to public assistance programs. These results do suggest that the intensity of the local health department's response is potentially an important determinant of long-term benefits and are consistent with prior evaluations of early life programs. Our point estimates of the lower intensity intervention suggest some benefit, but are not

[46] We calculated heterogeneous effects across different demographic groups, but these estimates are noisy due to a small number of individuals eligible for treatment in each subsample. For example, the number in the intervention group whom have birth records indicating a parent without a high school degree is 25. Overall, these estimates suggest slightly larger benefits for female children and those with parents who did not graduate from high school. Larger treatment effects for females are also found across evaluations of other early childhood interventions (Anderson 2008).

Table 5—Heterogeneous Effects by Intensity of Intervention

	Education index	Behavior index
	(1)	(2)
Panel A		
Intervention (20+)	0.295	−0.276
	(0.161)	(0.121)
Intervention (15+)	−0.069	0.056
	(0.124)	(0.110)
Intervention (10+)	0.068	−0.152
	(0.073)	(0.094)
Observations	301	301
Panel B		
Intervention × Large drop in BLL	0.102	−0.223
	(0.135)	(0.095)
Intervention	0.091	−0.128
	(0.069)	(0.086)
Observations	301	301
Panel C		
Intervention × Quick time to next BLL test	0.107	−0.080
	(0.172)	(0.127)
Intervention	0.105	−0.175
	(0.069)	(0.082)
Observations	301	301

Notes: This table presents results by different measures of the intensity of the potential intervention. All regressions include the full set of control variables listed in the table notes of Table 4. In panel A, we include indicators for potentially higher intensity treatment categories based on thresholds outlined in CDC recommendations summarized in Figure 1. We create indicators for those within the treatment group who have a test above 15 μg/dL and those with a test above 20 μg/dL. Note that these indicators are not mutually exclusive. An individual with a confirmatory test over 20 would have each of the three treatment level indicators equal to one. For panels B and C, we test for heterogeneous effects for other measures potentially capturing the intensity of the response to confirmed elevated blood lead levels. In panel B, we define large drop as those individuals that see a drop in BLL of more than 5 BLL between the second and third test. In panel C, we define quick time between second and third test based on less than one month between second (confirmatory) test and a third BLL test.

statistically significant, which is not surprising given the general lack of power to detect statistically significant effects on subsamples of our treatment group.[47]

Following a second elevated BLL test result, nearly 80 percent of individuals continue to get tested until their BLLs drop below the alert threshold of 10 μg/dL. While some individuals may test below the threshold due to mean reversion of inaccuracy in testing, many likely have lower BLLs due to some effort to reduce the risk of exposure in the residential environment. Reduction in exposure could be due to a parental response to information provided through discussions with health workers following a confirmatory elevated BLL test result or through instructions provided following a home-environment inspection. Reduction could also be due to

[47] While an important aspect of the lower intensity interventions is parental education about ways to control household exposure, they also provide nutritional information and a referral to remediation services. Thus, these estimated (imprecise) benefits are not inconsistent with previous randomized control trials that do not find large or significant BLL reductions when evaluating parental education and "household dust control" interventions (Campbell et al. 2011; Yeoh et al. 2009; Brown et al. 2006; Jordan et al. 2003; Lanphear et al. 1999).

the provision of remediation services following a home investigation or a referral to available remediation programs.

The most immediate (and expensive) way to reduce environmental exposure within residences identified to contain a lead hazard is through a remediation service. Prior evaluations of household lead remediation programs through randomized controlled trials document significant decreases in levels of household dust (Sandel et al. 2010) and the number of elevated BLL cases (Jones 2012). If an inquiry or home investigation identifies a potential residence-based hazard for children exceeding the alert threshold, families are typically referred to lead-based paint removal programs. Since 1998, LeadSafe Charlotte, a HUD-funded organization, has provided remediation services to eligible families. While we obtained application and remediation data from this program and are able to match to Charlotte properties, our estimation sample spans birth cohorts between 1990 and 1997, so we cannot match most individuals to remediation services closely following elevated test results. However, we do find a positive association between intervention and whether the parcel was eventually remediated through the LeadSafe Charlotte program in column 5 of Table 3. The magnitude of this coefficient indicates that intervention households were more than three times as likely to have lead remediation as our control group.

To further investigate whether benefits may be due to reductions in levels of exposure, Table 5 compares estimated intervention benefits across individuals in the intervention group who are more likely to have directly addressed lead exposure problems. First, we find larger effects for individuals experiencing a significant drop (more than 5 μg/dL) between the second and third BLL test. Individuals who experience a sharp drop in BLLs after two consecutive tests over the alert threshold are more likely to have benefited from a reduction in exposure.[48] We also estimate separate intervention effects for individuals who respond quickly by retesting within one month following a second test over the alert threshold. The direction of both of these estimates suggests benefits from directly addressing exposure risk.

We also compare outcomes across those living in a "treatment" or control parcel *after* the child in our estimation sample. Table 6 presents results from a specification where individuals living in an intervention parcel after the time of intervention are generally better off along education and behavioral outcomes compared to those living in control households. Also, as discussed earlier, we did not detect any difference in outcomes for individuals matched to the intervention and control parcels *prior* to BLL testing of our estimation sample. Again, these results mildly suggest that parcels containing a child in the intervention group experience long-term lead exposure reductions.

[48] One may be concerned that with measurement error in BLL tests, an initially high BLL test would be followed by mean reversion for a second test. Since we focus on drops between the second and third tests, the presence of two high BLL tests is more indicative of high lead exposure rather than just inaccuracies in testing. Additionally, variation in testing results and subsequent drops in BLL values would only serve to bias the coefficients for Table 5 towards zero.

Table 6—Educational and Behaviorial Differences for Prior and Future Residents

	Education index (1)	Behavior index (2)
Panel A. Prior residents		
Intervention parcel	0.030	0.001
	(0.049)	(0.047)
Observations	1,363	1,363
Panel B. Future residents		
Intervention parcel	0.100	−0.133
	(0.076)	(0.093)
Observations	430	430

Notes: This table reports the estimated difference in the summary index outcomes for children not included in our analysis but who were living in the treatment and control parcels either before or after the children included in our estimation sample. Panel A presents results for individuals that lived at the same address prior to our sample of treatment and control observations, while panel B presents results for individuals living at the same address after our estimation sample. We drop any parcels that contain both treatment and control observations. All regressions include the full set of control variables listed in the table notes of Table 4.

VI. Benefit-Cost Discussion

An important question from a policy perspective remains as to whether the benefits from the elevated BLL intervention outweigh the typical costs of the intervention. While a comprehensive benefit-cost analysis is not feasible in our setting since we cannot yet estimate effects on key outcomes such as employment and earnings, we provide a rough comparison of the typical intervention benefits and costs drawing from previous evaluations of early childhood interventions and estimates of typical costs from administrators of the relevant social service programs in Charlotte.

We estimate the average cost of an elevated BLL intervention in Charlotte at $5,288. This estimate includes the following components: a doctor's appointment including nutritional assessment/counselling, three follow-up BLL tests, a home environmental inspection, remediation of lead-based paint hazards by *LeadSafe Charlotte*, and the costs of case management through the Child Development Services Agency. We obtain the information on the costs for each of these components as well as an estimate of the probability the cost is incurred by an individual with two BLL tests over the 10 μg/dL threshold. This information and the sources for each element are detailed in Table 7.

For an estimate of the intervention benefits, we rely on prior work by Aos et al. (2004) who provide a detailed meta-analysis of the costs and benefits associated with prevention and early intervention programs for youth. Among more than 30 programs reviewed under the category *Early Childhood Education for Low Income 3- and 4-Year Olds*, Aos et al. (2004) calculate an adjusted effect size of 0.08 standard deviation increase in test scores and a 0.162 standard deviation decrease in crime for this category of programs.[49] These estimated program effects are very

[49] See Table C.1a (page 16) of Aos et al. (2004).

Table 7—Estimated Costs of Elevated BLL Intervention

	Cost	Pr(Cost)	Est. cost
Medical costs			
Doctor's visit/nutritional assessment	\$250	1	\$250
Additional BLL tests (× 3)	\$225	1	\$225
Home inspection and remediation			
Home inspection	\$650	1	\$650
Lead-based paint remediation	\$7,300	0.073	\$533
Social services cost			
Child developmental services/case management (3yrs)	\$9,000	0.403	\$3,630
Total estimated cost			\$5,288

Notes: Cost figures and most probability calculation are based on detailed conversations with social service providers in Mecklenburg County, North Carolina. Probabilities and costs of lead testing come from the North Carolina Children's Environmental Health Branch of the Department of Health and Human Services. Information on the costs of social services is from Mecklenburg County Children's Developmental Services. Information on lead remediation costs is based on HUD grant reporting records from Leadsafe Charlotte. Leadsafe remediation probability based on estimated probabilities for our intervention group given by Table 3.

similar to our primary estimated effects of 0.117 standard deviation increase in test scores and a 0.184 standard deviation decrease in antisocial behavior (including crime). Given the close proximity of these effect sizes, we draw directly from the estimated benefit calculation from the test score increase and crime decrease in Aos et al. (2004). Aos et al. (2004) estimates the change in expected lifetime earnings associated with a test score improvement of 0.08 standard deviation of \$4,917, and the total social cost savings associated with a 0.162 standard deviation decrease in crime is estimated to be \$4,749.[50] Applying these estimated benefits to our setting implies at least \$9,666 in benefits due to test score improvements and crime reduction associated with the elevated BLL intervention. Comparing this to the typical program costs in Table 7 and scaling up the cost estimate by 1.3 to account for the marginal deadweight loss of raising public funds to pay for the intervention (Poterba 1996), the benefit-cost ratio is 1.4:1. In other words, each \$1 invested in children with confirmed elevated blood lead levels yields a return of nearly \$1.40 based on our rough (and largely conservative) estimates drawing from prior evaluations interventions for children of similar age and socioeconomic background as those in our estimation sample.[51]

VII. Conclusion

In this first evaluation of the standard public health response to high levels of exposure to environmental lead, we find evidence that interventions can affect long-term educational and behavioral outcomes. We estimate far-reaching decreases in

[50] See the *Early Childhood Education for Low Income 3- and 4-Year Olds: Summary of Estimated Benefits and Costs* table on page 94 of Aos et al. (2004) and Appendix D starting on page 33 od Aos et al. for a detailed explanation of the benefit calculations for each category.

[51] This is likely a conservative estimate since it ignores any savings associated with improved health and reduced behavioral problems in school as well as benefits from any spillover effects within classrooms and communities. Moreover, we measure intention-to-treat estimates so the treatment effects would further be scaled up by the rate at which the population complies with the recommended interventions.

antisocial behaviors (suspensions, school crimes, unexcused absences, and criminal activity) and, to a lesser extent, increases in educational performance. These results support recent evidence that early life interventions can mitigate and compensate for the deleterious effects of lead.

A massive amount of evidence across multiple disciplines consistently points to a lasting negative impact of lead exposure. In fact, recent studies and media reports suggest that reductions in lead exposure through the prohibition of leaded gasoline may be one of the most important determinants of the decline in crime rates over the past two decades in the United States and other developed nations.[52] However, not much is known as to what types of programs and policies are effective in addressing these effects. While randomized controlled trials have been used to evaluate other large-scale early childhood interventions (e.g., Head Start), this paper demonstrates that evaluations of interventions related to lead exposure can be conducted using administrative data and by exploiting institutional features (such as testing procedures) to construct a valid counter-factual or control group to evaluate causal effects of intervention.

Although exposure to lead has been reduced in most countries due to the prohibition of leaded gasoline, lead exposure still represents a major public health issue. In the United States, children have continued to be exposed to lead over the last several decades as a result of deteriorating lead paint and contaminated dust within older housing units (Dixon et al. 2009, Gaitens et al. 2009, Levin et al. 2008). The National Survey of Lead and Allergens in Housing estimated that 38 million housing units in the United States (40 percent of all housing units) contained lead-based paint, and approximately 24 million had significant lead-based paint hazards (Jacobs et al. 2002). Recognizing the current threat to child health and development in California, a Superior Court judge recently ordered three paint companies to contribute \$1.15 billion to fund the inspection, risk assessment, and hazard abatement of older homes in 10 California jurisdictions (Superior Court of California, County of Santa Clara 2014).[53]

Lead exposure is a more pressing public health issue in developing countries where lead in petrol, industrial emissions, paints, ceramics, food and drink cans, water pipes, and traditional medicines is more prevalent. In an evaluation for the World Health Organization, Prüss-Üstün et al. (2004) estimates that 120 million people have blood lead concentrations above 10 μg/dL, accounting for an estimated 0.9 percent of the global burden of disease. Prüss-Üstün et al. (2004) also estimates that nearly 10 percent of children under five in the world have blood lead levels greater than 20 μg/dL with 99 percent of these children living in developing countries. There is a great deal of evidence that these levels of exposure cause drastic cognitive and behavioral impairment and policies to reduce exposure in developing countries should be of first-order importance.

Until countries and communities make long-run investments in reducing environmental exposure, our results suggest that intervening early is critical to limit the damage from exposure. Our research can be used to inform policymakers considering

[52] Recent media articles Drum (2016) and Monbiot (2013) highlight this connection based on results from papers by Mielke and Zahran (2012); Nevin (2007); Reyes (2007); Nevin (2000).

[53] Judgement was issued for the plaintiff, the People of the State of California, against defendants ConAgra Grocery Products Company, NL Industries, Inc., and The Sherwin-Williams Company.

intervention at lower levels of detected exposure. In 2012, the CDC recognized a lack of evidence for any BLL to be considered "safe" and recommended using a lower threshold to identify children at increased risk for health and developmental problems caused by exposure to lead (CDC 2012).[54] It is likely that increasing the frequency and intensity of intervention for lead-exposed children will yield a profound return considering the potential long-term effects of lead on health and human capital.

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[54] The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch currently provides more information about nutrition and key sources of exposure for children testing over 5 μ g/dL. The European Food Safety Authority and the World Health Organization have also recently concluded that there is no known safe level of exposure (Budtz-Jørgensen et al. 2013).

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